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Subseasonal Vacillations in the Winter Stratosphere

S. C. Hardiman[1], **A. A. Scaife**[1,2], **N. J. Dunstone**[1], **and L. Wang**[3]

[1]Met Office Hadley Centre, Exeter, UK, [2]College of Engineering, Mathematics, and Physical Sciences, University of Exeter, Exeter, UK, [3]Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

Key Points:

- Simple sine wave fits capture two thirds of interannual variance in monthly Northern Hemisphere winter stratospheric polar vortex strength
- Amplitude of these vacillations increases with planetary wave driving, consistent with wave-mean flow interaction theory
- Simple model skillfully predicts the stratospheric polar vortex strength at one month lead time

Correspondence to:
S. C. Hardiman,
steven.hardiman@metoffice.gov.uk

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Abstract Simple models of wave-mean flow interaction in the Northern Hemisphere winter stratosphere suggest the existence of subseasonal vacillations in the strength of the polar vortex. Here, we define a sinusoidal fit to the daily deseasonalized stratospheric wind. A suitable fixed period and amplitude for the sine waves is identified. Their mean value, equivalent to polar vortex strength, and phase, equivalent to the timing of sudden stratospheric warmings during winter, varies from year to year. These vacillations explain much of the subseasonal and interannual variability in the monthly mean vortex strength and, consistent with wave-mean flow interaction theory, their amplitude correlates positively with the magnitude of winter mean planetary wave driving. Furthermore, they allow skillful prediction of the vortex strength one month ahead. Identifying and understanding this subseasonal variability has potential implications for winter seasonal forecasts, as the December–February mean behavior may miss important subseasonal events.

1. Introduction

The anomalous, or deseasonalized, strength of the Northern Hemisphere winter stratospheric polar vortex has been shown to vacillate throughout the season, in both an idealized model (Holton & Mass, 1976; Yoden, 1987), referred to as the “Holton-Mass model”, and simple general circulation models (Christiansen, 1999; Gray et al., 2003; Hardiman & Haynes, 2008; Scaife & James, 2000). It is well known that planetary wave driving acts to weaken the strength of the polar vortex (Haynes et al., 1991; Kidston et al., 2015; Matsuno, 1971). Easterly winds then act to allow fewer planetary waves to enter the stratosphere, allowing the vortex strength to increase due to radiative effects, thus completing the vacillation cycle (Holton & Mass, 1976). This behavior, whereby planetary waves and the zonal mean flow act to influence the behavior of each other, is termed wave-mean flow interaction. It has been shown in the Holton-Mass model that greater planetary wave driving leads to both a weaker mean vortex strength (Figure 3 of Yoden, 1987) and also to the potential for this weakening of the vortex to occur earlier in the winter season (Figure 5 of Yoden, 1987). These vacillations have also been used to explain the basic difference between the Northern and Southern Hemisphere polar vortices (Scaife & James, 2000).

The vacillating nature of the stratospheric zonal mean wind offers the possibility of a simple model of subseasonal predictability of the stratospheric polar vortex strength. In addition, surface predictability of the North Atlantic Oscillation (NAO) may follow due to the downward propagation of zonal wind anomalies and their projection onto mean sea level pressure (Kidston et al., 2015). In the extreme case, planetary wave driving leads to sudden stratospheric warmings (SSWs; Andrews et al., 1987; Birner & Williams, 2008; McIntyre, 1982), a collapse of the stratospheric polar vortex, and a predictable drift to negative NAO (Scaife et al., 2016; Sigmond et al., 2013).

In this study, we formulate a simple sine wave fit to the observed deseasonalized (anomalous) daily zonal mean zonal wind in the stratosphere. We consider how much of the subseasonal variability in the wind, and how much of the interannual variability in monthly mean vortex strength, is captured by this simple model. We then test the predictive skill of this model, throughout the winter, against the simplest possible model—persistence of the vortex strength–and against a state-of-the-art seasonal forecasting system.

2. Description of Data Sets and Seasonal Forecasting System

The stratospheric wind used in this study to define the strength of the stratospheric polar vortex is daily zonal mean zonal wind, U, at 10 hPa, area-averaged 55–65°N (Butler et al., 2015; Charlton & Polvani, 2007). We use the extended winter period, November–March, for the 39 years 1979/1980–2017/2018 from the ERA-Interim reanalysis data set (Dee et al., 2011). The winds are deseasonalized using the method developed by MacLachlan et al. (2015). Using the climatological (i.e., average across all years) daily U data, a rolling 61 day mean is formed (i.e., $\pm$30 days), weighted with the function

$$w = e^{-d^2/100} \tag{1}$$

where d is the lag/lead in days from the central day (i.e., an exponential decay on a time scale of 10 days). This climatological daily rolling mean is then removed from the daily winds for each year, producing the anomalous daily wind field. This method reduces daily sampling variability and is smoother than removing climatological daily means. It also retains the variability we wish to study, while removing the climatological seasonal cycle. Throughout the remainder of the paper, U refers to this deseasonalized (anomalous) daily wind.

Operational seasonal hindcasts are from the Met Office Global Seasonal forecast system version 5 (GloSea5; MacLachlan et al., 2015), using the Global Coupled version 2 configuration of the climate model, as detailed in Williams et al. (2015). The atmosphere and land surface model horizontal resolution is $0.833° \times 0.556°$, and the ocean and sea ice model horizontal resolution is 0.25°. The ensemble mean of a seven-member hindcast ensemble is used, with members initialized on the 25th of the month prior to that being forecast (i.e., forecasts of January use the mean of a seven-member ensemble initialized on 25 December), for each of the 23 hindcast years (1993/1994–2015/2016). Due to the signal-to-noise issue (Scaife & Smith, 2018) currently manifest in most forecasting systems (Baker et al., 2018), an ensemble mean is necessary to more accurately represent the inherent skill in the seasonal forecasting system.

The NAO index (Cropper et al., 2015) is defined as the difference in mean sea level pressure between 335°E and 39°N (the Azores) and 339°E and 65°N (Iceland), using ERA-Interim, and GloSea5 mean sea level pressure data.

3. Results

3.1. Formulating the Sine Wave Model

In order to define our simple sine wave fitting model, we first fit to the deseasonalized zonal mean zonal wind data, U, by allowing four free parameters:

$$U = a + b\ \sin(c(x + d)) \tag{2}$$

the offset (or mean; a (m s^{-1})), amplitude (b (m s^{-1})), phase (d (days)), and period ($2\pi/c$ (days^{-1})) of the sine waves. For each year, all the daily U data in the period November–March are used. We find that, across all years, the offset of these sine waves is negatively correlated to their amplitude (correlation coefficient = −0.36; note that when using 39 years of data, any correlation with magnitude greater than 0.32 is statistically significant at the 95% level, using the Student's t test). This is consistent with wave mean-flow interaction theory (Holton & Mass, 1976), since both a positive offset (strong vortex) and reduced amplitude would be indicative of reduced planetary wave driving. We also find the offset to be negatively correlated to the phase of these sine waves (correlation coefficient = −0.39). Since a negative phase, by construction, is equivalent to a weakening of the vortex occurring later in the winter period, this is also consistent with reduced planetary wave driving (see, e.g., Figure 5 of Yoden, 1987).

These results are reassuring but, having obtained them, there is good reason to reduce the number of free parameters in the model before going further. The more free parameters in a model, the easier it is to form a "good" fit to any given distribution. One of the key aims of this work is to demonstrate that, as predicted by simple models and wave-mean flow interaction theory, a sine wave is a good fit to anomalous winds in the winter stratosphere. It is necessary to retain free parameters for the offset of the sine wave (a measure of the winter mean vortex strength) and also the phase (a measure of when, during the winter, an SSW might occur). Thus, a choice of fixed period length and fixed wave amplitude must be made. Of course, not all Northern Hemisphere winters experience SSWs, and so, in those years that do not, the phase is simply an indication of when, during the winter, the (deseasonalized) vortex strength is weakest.

Considering the four-parameter sine wave fits to all 39 years of ERA-Interim winds, the histogram of periods in the range 80–200 days is fairly uniform in the interval 80–160 days but suggests a preference for a period

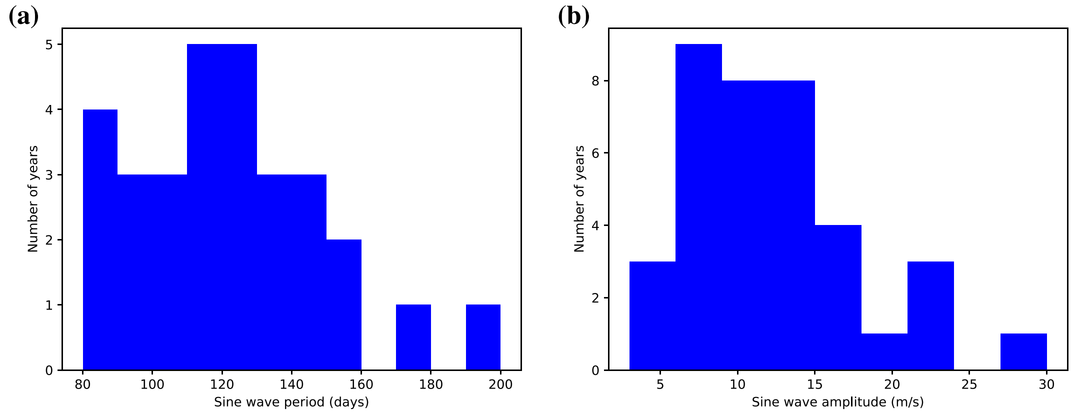

Figure 1. (a) Histogram (using 10 day bins) of the periods from a four-parameter sine wave fit to deseasonalized daily zonal mean zonal wind, *U* (10 hPa, 55–65°N), for months November–March and years 1979/1980–2017/2018, using the ERA-Interim reanalysis. (b) Histogram (using 3 m s^{-1} bins) of the amplitudes from a three-parameter sine wave fit, using a 120 day fixed period.

in the range 110–130 days (Figure 1a). Thus, we fix the period to be 120 days (close to the mean period of 122.3 days) for the remainder of the study (the results below do not depend on the exact length of period chosen). This length of period is consistent with the 80–130 day periods found in the general circulation model control experiments of Christiansen (1999), and with the work of Sjoberg and Birner (2014) who incorporated a realistic (planetary wave flux based) bottom boundary condition into the Holton-Mass model. This leaves three free parameters (offset, amplitude, and phase). Fitting sine waves to daily *U* data for each winter, using this three-parameter model, we find further evidence of a link between the fitted sine waves and planetary wave driving. We define planetary wave driving as the December–February mean of the Wave 1 component of geopotential height at 100 hPa (Hardiman et al., 2008) and averaged 45–75°N (Newman et al., 2001), though results are insensitive to the exact choice of latitudes. This correlates positively with the amplitude of the fitted sine waves (correlation coefficient = 0.37), and negatively with their offset (correlation coefficient = −0.63) as expected. No preferred sine wave amplitude is found. The histogram of amplitudes in the range 5–30 m s^{-1} is uniform in the interval 6–15 m s^{-1}, tailing off for higher amplitudes (Figure 1b). In what follows we fix the amplitude to be 12.0 m s^{-1} (close to the mean amplitude of 11.9 m s^{-1} and consistent with Figure 3a of Shiotani et al., 1993). Again, the results do not depend on the exact amplitude chosen.

This defines our two-parameter model, with offset (or mean vortex strength) and phase (or SSW timing) as the free parameters. Figure 2 shows the raw deseasonalized *U* data and the two-parameter sine wave fits to this data. For brevity, only the first 6 of the 39 years are shown, but they are representative of the fit in all other years. It can be seen that the sine wave fit captures much of the subseasonal variability. The average correlation (across all 39 years) between the daily *U* data (for all 151 days in November–March) and the daily values of the sine wave fit to this data is 0.65. To put this in context, the simplest two-parameter fit to the data would be linear ($U = a + bx$), and the average correlation (across all 39 years) between the daily *U* data and this linear fit is 0.28. In order to quantify the interannual variability captured by these sine wave fits, Figure 3 shows, for each month, the monthly mean 39 year time series for the deseasonalized *U* data and the monthly means of the sine wave fits to this data. The interannual correlations between these two time series are given in Figure 3 and it can be seen that, throughout December–February, they are greater than 0.8 (so capturing around two thirds of the interannual variance). To put these values in context, Table 1 compares the correlations given in Figure 3 with interannual correlations obtained from comparing the deseasonalized *U* data to its winter (November–March) mean values. The null hypothesis, that the anomalous strength of the stratospheric polar vortex remains constant throughout each winter period, is a consistently worse fit to the data in all months (Table 1). The probability of any process (which performs equivalently to persistence) randomly beating persistence in all five months is $1/2^5$—less than 5%. Thus, it is highly likely that the sine wave fit performs better than persistence and, furthermore, correlations are increased by more than 0.2 in all five months when using sine wave fitting. The average correlation across December–February is 0.90 for the sine wave fit, as compared with 0.66 for the winter mean, and 0.79 for the linear fit. The fact that these

10.1029/2020GL087766

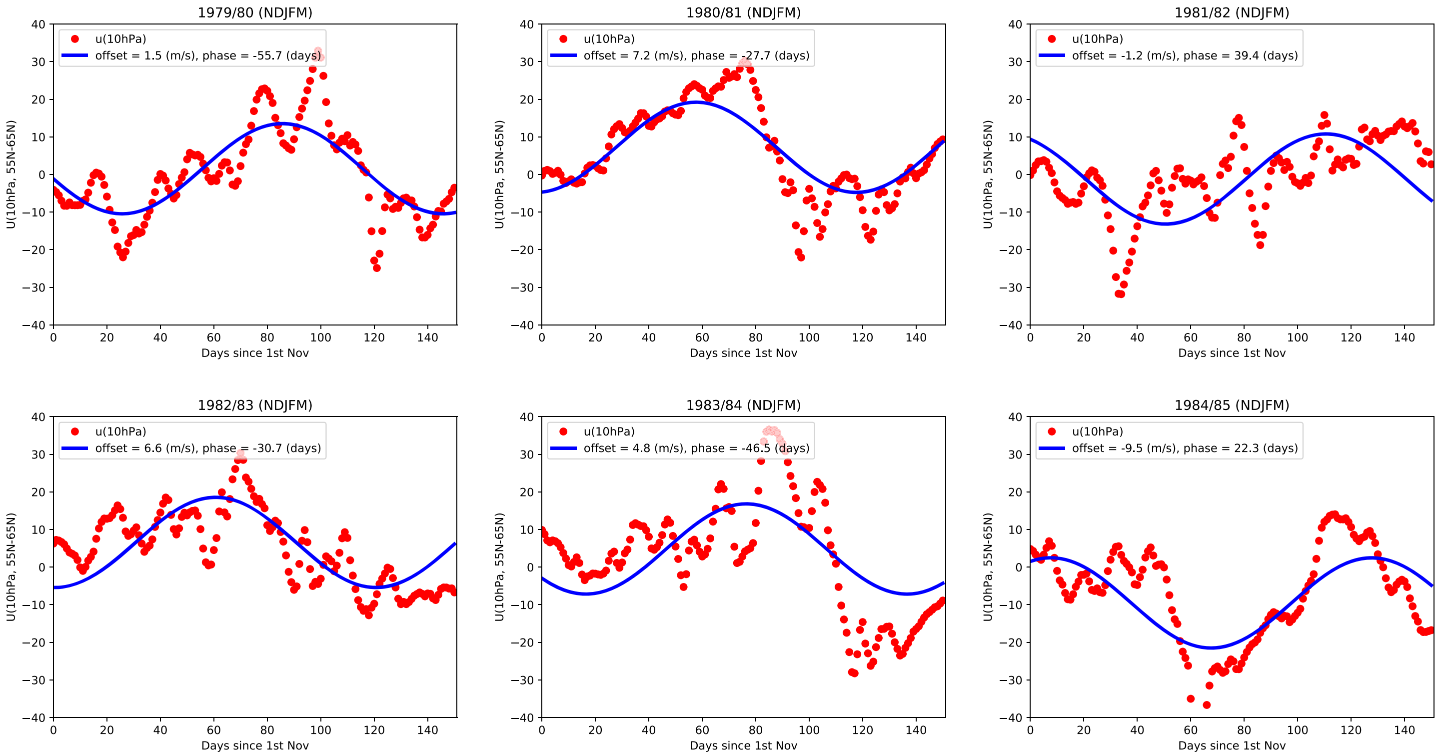

Figure 2. Deseasonalized daily zonal mean zonal wind, U (10 hPa, 55–65°N), for example Northern Hemisphere winters 1979/1980–1984/1985, using the ERA-Interim reanalysis (red dots), and the corresponding two-parameter sine wave fit, using fixed 120 day period and 12 m s^{-1} amplitude (blue curves). The sine wave fit for each year is to the daily data for all five months, November–March. The offset and phase of each sine wave fit is displayed in the figure panels. Winters 1979/1980–2017/2018 ((a)-(f)) are used, with the first 6 years shown as an example (they are representative of the fit in all other years).

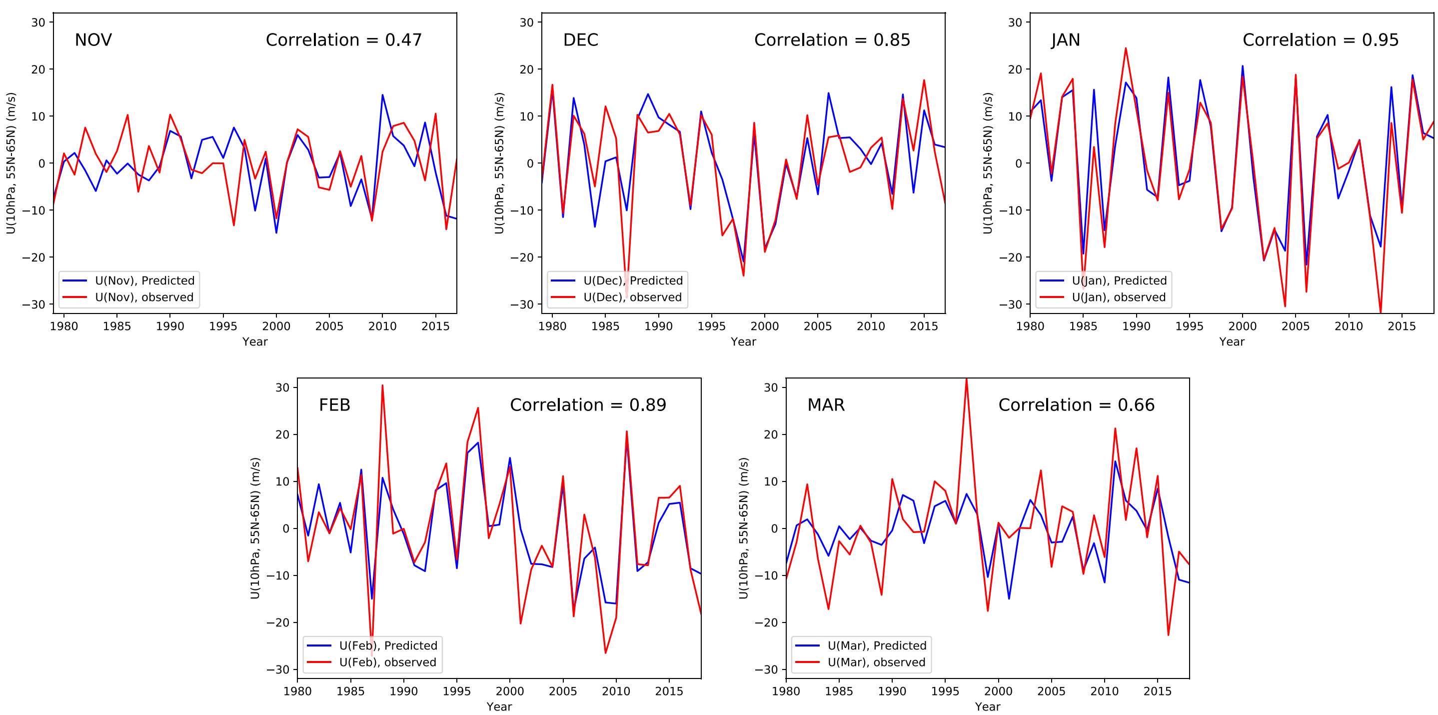

Figure 3. Time series of *monthly* mean deseasonalized U data (red curves) and corresponding time series of the *monthly* mean of the sine wave fit to the daily November–March ((a)-(e)) deseasonalized U data for each year (blue curves), using the two-parameter (offset and phase) sine wave fit shown in Figure 2. Interannual correlations between the two time series are displayed, for each month, in the figure panels.

10.1029/2020GL087766

Table 1
Correlations to Monthly Mean U, Using All Data From November–March

Month	Nov	Dec	Jan	Feb	Mar
Sine fit	0.47	0.85	0.95	0.89	0.66
Winter mean	0.22	0.61	0.71	0.65	0.13

interannual correlations are so high for the sine wave model demonstrates, again, how well the sine wave fit does in each individual year at capturing the subseasonal variability throughout November–March.

3.2. Predictable Vacillations

Now, considering predictability, we try fitting a sine wave using the above defined two-parameter model, in any given year, only using deseasonalized U data for the months preceding that which we are trying to predict. So, for example, to predict January, we try fitting to December and also to November–December daily data. We then correlate the monthly mean multiannual time series of the sine fit for January with the monthly mean U data for January. It is found that, in the case of all five winter months, the best predictability for any given month is found by fitting a sine wave to U data for just the single preceding month (e.g., using data for the single month of December 1990 in the case of predicting January 1991). The interannual correlations thus obtained are given in Table 2. All these correlations, ranging from 0.35 to 0.66, are statistically significant at the 95% level, and they therefore demonstrate skillful predictions. Table 2 also shows the correlations obtained using "persistence." Here we define persistence by assuming that the monthly mean vortex strength does not change from one month to the next and so, in the example above, a time series of the December mean deseasonalized U wind is correlated with a time series of the January mean deseasonalized U wind to give the skill for January (i.e., a correlation of 0.44 as shown in Table 2). The sine wave fitting model beats persistence in four out of the five months, and so we can say with reasonable confidence that this model gives better skill of the anomalous vortex strength than does persistence.

We now compare with the Met Office operational dynamical seasonal forecasting system, GloSea5. Interannual correlations are given in Table 2, for the sine wave fits and for GloSea5, using just the years 1993–2015 for which GloSea5 data are available (see section 2 for details). GloSea5 comfortably beats the skill of the sine wave fits in all five months and shows an average correlation of 0.76. Thus, while the sine wave fits show skill that beats persistence, this simple model cannot be used in place of a state-of-the-art dynamical seasonal prediction system. Furthermore, the linear fit discussed in the previous section ($U = a + bx$) offers comparable predictability to the sine wave fit (not shown). Thus, while the sine wave fit has been shown to capture the subseasonal variability across the whole winter very accurately (when fitting to all 151 days of daily data), the predictability offered by a sine wave fit (when using just 30 days of daily data) is not high. Recall also that GloSea5 is initialized on the 25th day of the month, and so it could be argued that a fairer comparison of GloSea5 against persistence would be to use persistence based on winds averaged over days 15–25 of the previous month (rather than the whole monthly mean)—this does not significantly change the values given for persistence in Table 2.

Given the link between stratospheric polar vortex strength and surface climate (Baldwin & Dunkerton, 1999; Kidston et al., 2015), an obvious question is whether this simple sine wave fitting model can also skillfully predict the monthly mean NAO index. There are a number of different predictors that can be used here: deseasonalized U winds in the previous month, sine wave fit (based on winds for the previous month), and persistence of the NAO index itself. For all of these methods, the interannual correlations calculated for all five months, November–March, average to 0.19. Thus, the sine fitting does not offer skillful prediction of the NAO index, nor does it offer any improvement over use of either the anomalous stratospheric winds or persistence of the NAO index. GloSea5 outperforms all these methods, with an average correlation of 0.49 across the five months, November–March, and an average correlation of 0.54 across the three months, December–February (consistent with Figure 4 of Scaife et al., 2016).

Table 2
Predictions of Monthly Mean U, Using Data From Single Preceding Month

Predicted month	Nov	Dec	Jan	Feb	Mar
Sine fit (1979–2017)	0.46	0.35	0.66	0.59	0.41
Persistence (1979–2017)	0.28	0.43	0.44	0.41	0.13
Sine fit (1993–2015)	0.38	0.19	0.63	0.59	0.50
GloSea5 (1993–2015)	0.74	0.64	0.76	0.82	0.86

4. Discussion/Conclusions

Wave-mean flow interaction theory, along with simple models of the stratospheric polar vortex (Holton & Mass, 1976; Scaife & James, 2000), paints a picture of the anomalous winter stratospheric winds vacillating in strength throughout the season, with a period of around 80–130 days (Christiansen, 1999). By constructing a sine wave fit to the deseasonalized daily zonal mean zonal winds at 10 hPa and 55–65°N, this picture has been demonstrated to be consistent with the behavior of the winds in the ERA-Interim reanalysis data set. Vacillations in ERA-Interim are found to have an average period of 120 days (with the most common length of period falling in the range 110–130 days), and an average amplitude of 12 m s^{-1}. A sine wave fit, using these parameters, and two free parameters for the offset (mean) and phase of the vacillations during winter, captures around two thirds of the variance of the interannual variability in vortex strength on subseasonal time scales—more than is captured by using the simple "winter mean" value of the deseasonalized stratospheric vortex strength for each year or by a linear fit. The sine wave fits also capture the subseasonal variability in vortex strength well, correlating with the deseasonalized daily zonal mean winds with an average correlation coefficient of 0.65. By comparison, a linear fit to the daily winds correlates only with a coefficient of 0.28. Significant negative correlations of the offsets of the fitted sine waves with their amplitudes and phases, and significant positive/negative correlations of the amplitude/offset of the sine waves with planetary wave driving, are consistent with, and add confidence to, the theory of wave-mean flow interaction.

The two-parameter sine wave fit is found to offer skillful predictions of the monthly mean stratospheric polar vortex strength, with a 1 month lead time, beating the skill offered by "persistence" of the vortex strength in 4 out of 5 months (November–March), but offering only comparable skill to a linear fit. This simple model is also outperformed by the Met Office seasonal forecast system, GloSea5, in terms of predictions both of the monthly mean stratospheric vortex strength and the monthly mean NAO index. Nevertheless, the fact that so much of the variance in anomalous vortex strength is captured by sine wave fitting has potential implications for the commonly used December–February average when issuing winter seasonal forecasts, since subseasonal vacillations are a prominent source of variability in the winter stratosphere.

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References

Andrews, D. G., Holton, J. R., & Leovy, C. B. (1987). Middle atmosphere dynamics (p. 489). San Diego, CA: Academic.

Baker, L. H., Shaffrey, L. C., Sutton, R. T., Weisheimer, A., & Scaife, A. A. (2018). An intercomparison of skill and overconfidence/underconfidence of the wintertime North Atlantic Oscillation in multimodel seasonal forecasts. *Geophysical Research Letters*, *45*, 7808–7817. https://doi.org/10.1029/2018GL078838

Baldwin, M. P., & Dunkerton, T. J. (1999). Propagation of the Arctic oscillation from the stratosphere to the troposphere. *Journal of Geophysical Research*, *104*(D24), 30,937–30,946. https://doi.org/10.1029/1999JD900445

Birner, T., & Williams, P. D. (2008). Sudden stratospheric warmings as noise-induced transitions. *Journal of the Atmospheric Sciences*, *65*, 3337–3343. https://doi.org/10.1175/2008JAS2770.1

Butler, A. H., Seidel, D. J., Hardiman, S. C., Butchart, N., Birner, T., & Match, A. (2015). Defining sudden stratospheric warmings. *Bulletin of the American Meteorological Society*, *96*, 1913–1928. https://doi.org/10.1175/BAMS-D-13-00173.1

Charlton, A. J., & Polvani, L. (2007). A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks. *Journal of Climate*, *20*, 449–469. https://doi.org/10.1175/JCLI3996.1

Christiansen, B. (1999). Stratospheric vacillations in a general circulation model. *Journal of the Atmospheric Sciences*, *56*, 1858–1872. https://doi.org/10.1175/1520-0469(1999)056<1858:SVIAGC>2.0.CO;2

Cropper, T., Hanna, E., Valente, M. A., & Jónsson, T. (2015). A daily AzoresIceland North Atlantic Oscillation index back to 1850. *Geoscience Data Journal*, *2*, 12–24. https://doi.org/10.1002/gdj3.23

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*, 553–597. https://doi.org/10.1002/qj.828

Gray, L. J., Sparrow, S., Juckes, M., O'neill, A., & Andrews, D. G. (2003). Flow regimes in the winter stratosphere of the Northern Hemisphere. *Quarterly Journal of the Royal Meteorological Society*, *129*, 925–945. https://doi.org/10.1256/qj.02.82

Hardiman, S. C., & Haynes, P. H. (2008). Dynamical sensitivity of the stratospheric circulation and downward influence of upper level perturbations. *Journal of Geophysical Research*, *113*, D23103. https://doi.org/10.1029/2008JD010168

Hardiman, S. C., Kushner, P. J., & Cohen, J. (2008). Investigating the ability of general circulation models to capture the effects of Eurasian snow cover on winter climate. *Journal of Geophysical Research*, *113*, D21123. https://doi.org/10.1029/2008JD010623

Haynes, P. H., McIntyre, M. E., Shepherd, T. G., Marks, C. J., & Shine, K. P. (1991). On the downward control of extratropical diabatic circulations by eddy-induced mean zonal forces. *Journal of the Atmospheric Sciences*, *48*, 651–678. https://doi.org/10.1175/1520-0469(1991)048<0651:OTCOED>2.0.CO;2

Holton, J. R., & Mass, C. (1976). Stratospheric vacillation cycles. *Journal of the Atmospheric Sciences*, *33*, 2218–2225. https://doi.org/10.1175/1520-0469(1976)033<218:SVC>2.0.CO;2

Kidston, J., Scaife, A. A., Hardiman, S. C., Mitchell, D. M., Butchart, N., Baldwin, M. P., & Gray, L. J. (2015). Stratospheric influence on tropospheric jet streams, storm tracks and surface weather. *Nature Geoscience*, *8*, 433–440. https://doi.org/10.1038/NGEO2424

MacLachlan, C., Arribas, A., Peterson, K. A., Maidens, A., Fereday, D., Scaife, A. A., et al. (2015). Global Seasonal forecast system version 5 (GloSea5): A high-resolution seasonal forecast system. *Quarterly Journal of the Royal Meteorological Society*, *141*, 1072–1084. https://doi.org/10.1002/qj.2396

Matsuno, T. (1971). A dynamical model of the stratospheric sudden warming. *Journal of the Atmospheric Sciences*, *28*, 1479–1494. https://doi.org/10.1175/1520-0469(1971)028<1479:ADMOTS>2.0.CO;2

McIntyre, M. E. (1982). How well do we understand the dynamics of the stratospheric warming? *Journal of the Meteorological Society of Japan*, *60*, 37–65. https://doi.org/10.2151/jmsj1965.60.1_37

Newman, P. A., Nash, E. R., & Rosenfield, J. E. (2001). What controls the temperature of the Arctic stratosphere during the spring? *Journal of Geophysical Research*, *106*(D17), 19,999–20,010. https://doi.org/10.1029/2000JD000061

Scaife, A. A., & James, I. N. (2000). Response of the stratosphere to interannual variability of tropospheric planetary waves. *Quarterly Journal of the Royal Meteorological Society*, *126*, 275–297. https://doi.org/10.1002/qj.49712656214

Scaife, A. A., Karpechko, A. Y., Baldwin, M. P., Brookshaw, A., Butler, A. H., Eade, R., et al. (2016). Seasonal winter forecasts and the stratosphere. *Atmospheric Science Letters*, *17*, 51–56. https://doi.org/10.1002/asl.598

Scaife, A. A., & Smith, D. (2018). A signal-to-noise paradox in climate science. *npj Climate and Atmospheric Science*, *1*, 28. https://doi.org/10.1038/s41612-018-0038-4

Shiotani, M., Shimoda, N., & Hirota, I. (1993). Interannual variability of the stratospheric circulation in the Southern Hemisphere. *Quarterly Journal of the Royal Meteorological Society*, *119*, 531–546. https://doi.org/10.1002/qj.49711951110

Sigmond, M., Scinocca, J. F., Kharin, V. V., & Shepherd, T. G. (2013). Enhanced seasonal forecast skill following stratospheric sudden warmings. *Nature Geoscience*, *6*, 98–102. https://doi.org/10.1038/ngeo1698

Sjoberg, J. P., & Birner, T. (2014). Stratospheric wave mean flow feedbacks and sudden stratospheric warmings in a simple model forced by upward wave activity flux. *Journal of the Atmospheric Sciences*, *71*, 4055–4071. https://doi.org/10.1175/JAS-D-14-0113.1

Williams, K. D., Harris, C. M., Bodas-Salcedo, A., Camp, J., Comer, R. E., Copsey, D., et al. (2015). The Met Office Global Coupled model 2.0 (GC2) configuration. *Geoscientific Model Development*, *8*, 1509–1524. https://doi.org/10.5194/gmd-8-1509-2015

Yoden, S. (1987). Bifurcation properties of a stratospheric vacillation model. *Journal of the Atmospheric Sciences*, *44*, 1723–1733. https://doi.org/10.1175/1520-0469(1987)044<1723:BPOASV>2.0.CO;2